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HIGH THERMAL CONDUCTANCE DEVICES
UTILIZING
THE BOILING OF LITHIUM OR SILVER

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HIGH THERMAL CONDUCTANCE DEVICES
UTILIZING
THE BOILING OF LITHIUM OR SILVER

by

J. E. Deverall
J. E. Kemme

ABSTRACT

The "Grover Heat Pipe" is a self-contained, thermal conductance device that has no moving parts, utilizes the heat being transferred for its operation, has a thermal conductance higher than any known material, and conducts heat with essentially no temperature difference. Heat is transferred by means of mass flow of a fluid, utilizing the latent heat of a two-phase system.

For high-temperature applications, two liquid metals have been tested and found suitable as heat pipe fluids: lithium and silver. Lithium heat pipes have been successfully operated up to 1300°C with heat input fluxes of 200 watts/sq cm and silver heat pipes up to 2000°C with input fluxes of over 400 watts/sq cm.

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EFFECTIVE HEAT-TRANSFER DEVICES USING BOILING LITHIUM OR SILVER

I. INTRODUCTION

In high-temperature systems, many problems arise involving the transfer of heat. One such problem is the transfer of very high heat fluxes between components. Another is the production of isothermal conditions over relatively large areas or the concentration of high thermal energies to relatively small areas. In space applications, where heat can be rejected only by radiation, there is also the problem of transferring heat to a radiator system with a minimum temperature drop so that heat can be rejected at the highest possible temperature.

With the high heat fluxes of many present-day systems, heat flow by conduction, using the highest conductivity materials available, is much too low to meet requirements. Dimensional and weight limitations (especially prevalent in space applications) often make it impossible to provide large enough conduction paths for the required heat flow regardless of the material's thermal conductivity.

The Grover heat pipe[1], having a fraction of the weight of a solid conductor and orders of magnitude greater heat-transfer characteristics, appears to have great potential for the solution of heat-transfer problems. By replacing the heat flow mechanism of conduction with a fluid flow system utilizing latent heat, heat-transfer devices can be constructed that have several hundred times the thermal conductance per unit weight of any solid conductor (see Appendix A). By the proper

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[1]First reported in "Structures of Very High Thermal Conductance" by G. M. Grover, T. P. Cotter, and G. F. Erickson, J. Appl. Phys., 35, 1, 1964.

choice of fluids, heat pipes can be constructed for operating temperatures from below 0°C to over 2000°C.

II. PRINCIPLE OF OPERATION

The principle of heat transfer by a heat pipe is mass flow of a fluid utilizing its latent heat. The solid conductor is replaced by a hollow conductor containing a fluid that is continuously evaporating and condensing. A two-phase system is thereby established, and an essentially constant temperature is maintained throughout the length of the container.

Heat addition into one section of the heat pipe is distributed throughout the other section by flow and condensation of vapor. Completion of the cycle is obtained with the return of the condensate to the evaporator by capillary action through a wick structure. The driving force for the vapor is created by a higher vapor pressure in the evaporator section, due to the slightly higher liquid temperature at the heat input area (see Fig. 1).

In a two-phase system, the temperature is a function of vapor pressure. If a heat pipe is operated at a pressure that corresponds to a section of the vapor pressure curve having a steep slope, the pressure difference necessary for the vapor driving force produces a very small temperature drop along the length of the pipe (see Fig. 2).

Vapor flow is dependent upon the diameter and the length of the vapor passage, and on the kinematic viscosity of the vapor. The flow of liquid in the wick structure is dependent upon the viscosity, surface tension, and wetting ability of the liquid, and upon the pore size and flow resistance of the wick structure. In a gravitational field, the height to which a liquid can be wicked is also a function of liquid density. In free space, however, capillary action should be independent of heat pipe orientation.

III. REQUIREMENTS FOR HEAT PIPE FLUIDS

Based on the operating mechanisms and structure of a heat pipe, the desirable properties of heat pipe fluids are: 1) high latent heat, 2) high thermal conductivity, 3) low viscosity, 4) high surface tension, 5) high wetting ability, and 6) suitable boiling point.

1. <u>Latent Heat</u>: A high latent heat is desirable in order to transfer the maximum amount of heat with the minimum flow of fluid.
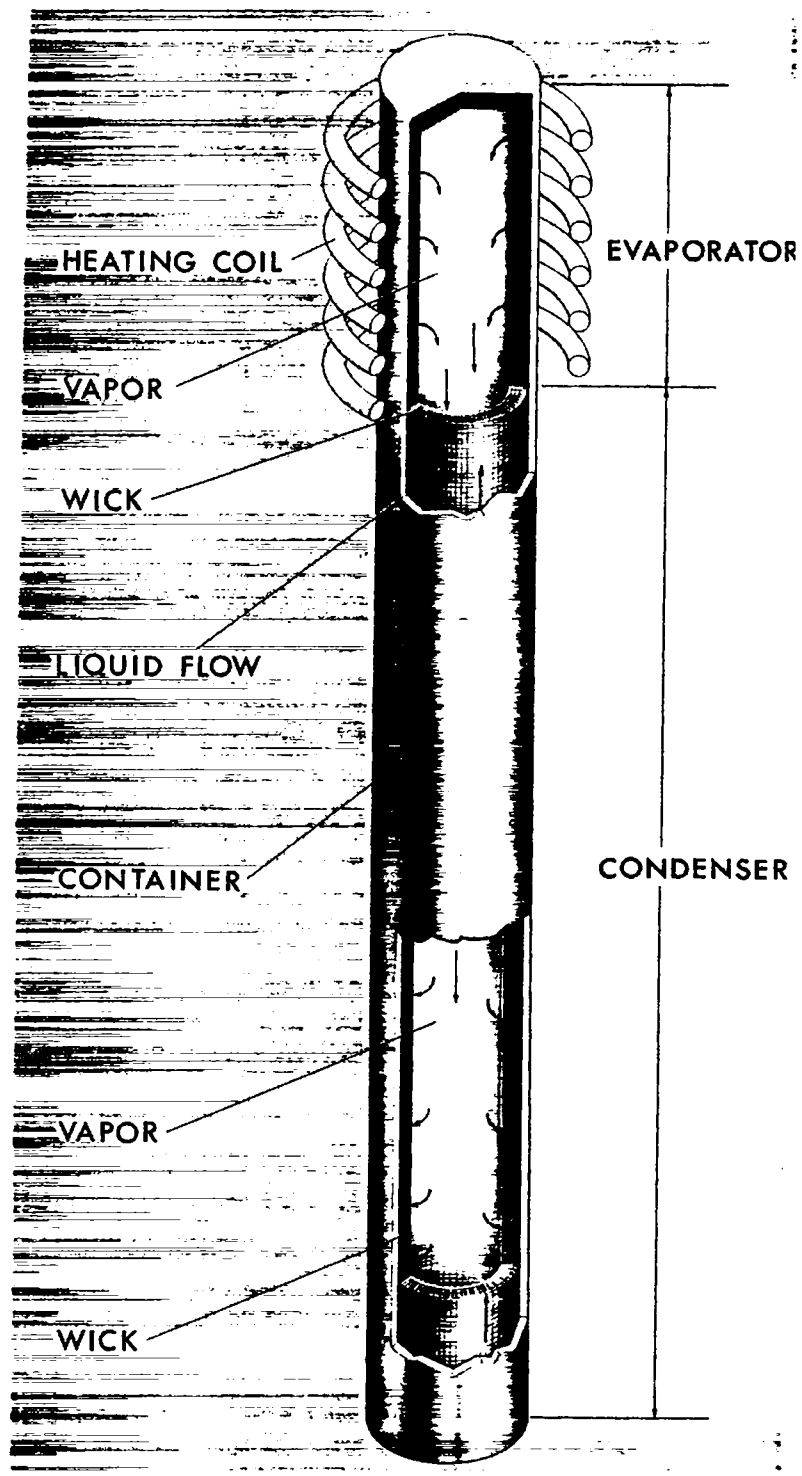
HEATING COIL

VAPOR

WICK

LIQUID FLOW

CONTAINER

VAPOR

WICK

EVAPORATOR

CONDENSER

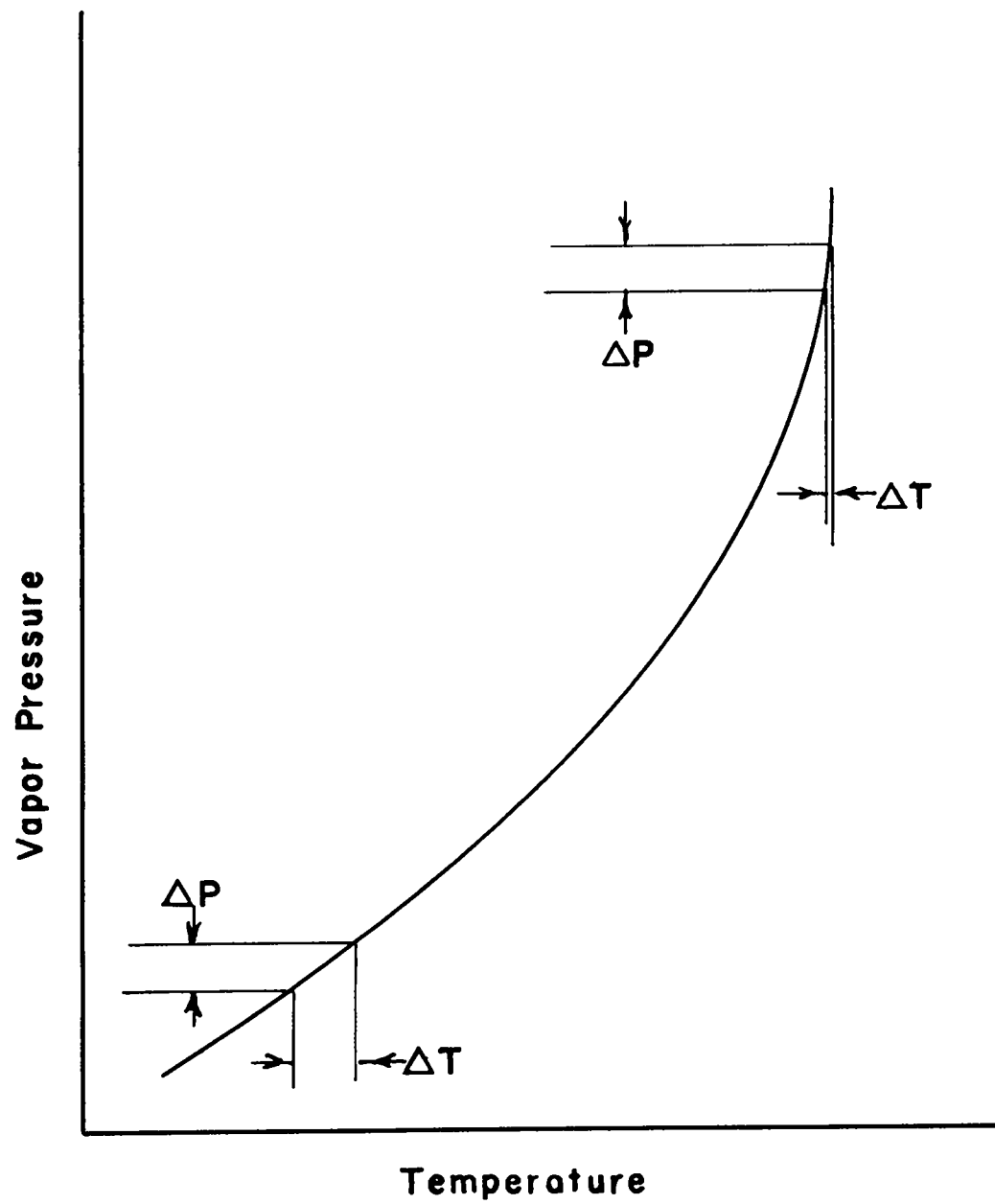Fig. 1. The "Grover Heat Pipe"

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Fig. 2. Vapor pressure/temperature curve

2. <u>Thermal Conductivity</u>: High thermal conductivity of the liquid minimizes radial temperature differences across the liquid layer in the evaporator wick section and reduces the possibility of localized boiling at the tube wall (see Fig. 3).

3. <u>Viscosity</u>: The viscosity of both the liquid and vapor should be low to present minimum resistance to circulation.

4. <u>Surface Tension</u>: The flow of liquid in the wick structure depends upon capillary action. The higher the surface tension, the better the wicking action.

5. <u>Wetting Ability</u>: The wick structure must be completely wet by the liquid in order for capillary action to function properly. Partial wetting results in inefficient operation and possible formation of hot spots in the evaporator section.

6. <u>Boiling Point</u>: The choice of fluid, based on boiling point, depends upon the desired operating temperature. At such temperature, the vapor pressure should be in the section of the pressure/temperature curve that produces essentially isothermal conditions. Too low vapor pressure results in inadequate driving force for the vapor; and, when there is insufficient vapor flow, large temperature gradients appear along the length of the heat pipe. On the other hand, pressures should not be so high that containment is a problem, as thin-walled tubes are desirable for radial heat transfer and weight economy. By the appropriate choice of fluids, a wide range of operating temperatures can be obtained with essentially isothermal conditions at reasonable pressures.

IV. HEAT PIPE CONSTRUCTION

The heat pipes reported here are relatively simple devices consisting of a sealed tube, a wick structure lining the internal surfaces, and sufficient fluid to completely saturate the wick. There is no reason, however, to limit heat pipe construction to cylindrical geometries.

The wick can be formed by any method that produces a capillary structure of interconnected pores or channels. One simple method is to roll fine-mesh screen into a cylindrical tube having as many layers of screen as desired. The tube is then inserted into the container and compressed against the container wall by pushing a steel ball through the assembly. Although there are some difficulties with this type of wick structure, the assembly is relatively simple, and fine-mesh screen is readily obtained in many different materials.
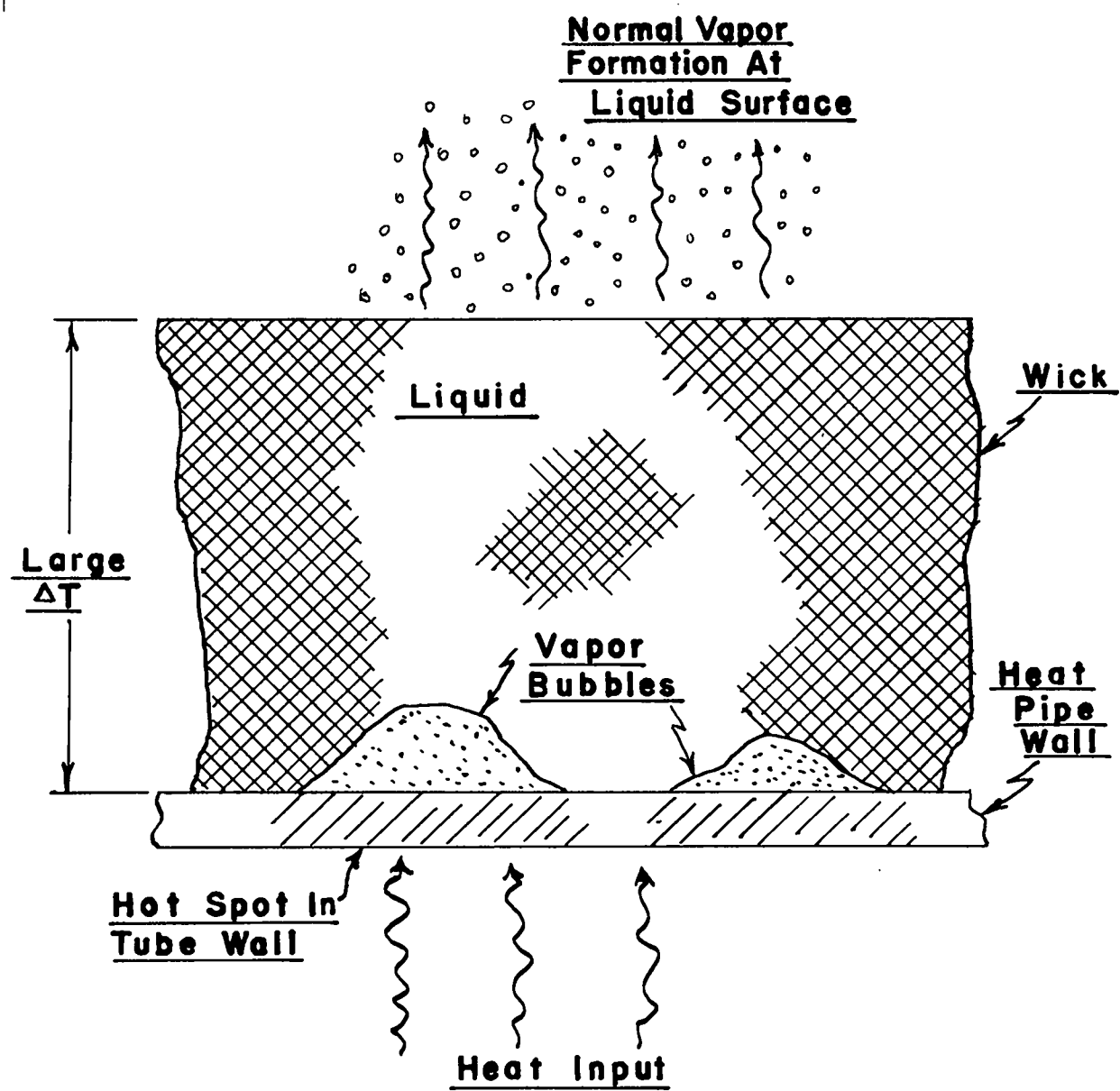
Fig. 3. Localized boiling at tube wall

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In the selection of container and wick materials, consideration must be given to compatibility with the fluid and to the ability of the fluid to wet the materials.

For proper operation of a heat pipe, it is important that there be no non-condensable gases in the system. This means that the pipe must be loaded and sealed under high vacuum. It is also necessary to have the materials out-gassed so that gases do not build up during operation. To promote wetting, all materials must be as clean as possible. In order to obtain clean, well out-gassed systems, the following procedure is used for lithium heat pipes and is similar for other types:

1. The wick, tube, and end caps are bright-dipped.
2. The wick, tube, and end caps are out-gassed at 1350°C.
3. The wick is inserted into the tube, and the bottom end cap is welded in.
4. The assembly is out-gassed at 1350°C.
5. Lithium is loaded in an argon atmosphere.
6. The top end cap is welded in.
7. A small hole is drilled in the top end cap.
8. The tube is evacuated overnight in an electron-beam chamber.
9. The hole is sealed by electron-beam welding.
10. The heat pipe is heated to 1300°C in a horizontal position, to completely wet the wick with lithium.

The out-gassing and wetting operations are carried out in the high-vacuum furnace shown in Fig. 4.

V. BOILING LITHIUM HEAT PIPES

Several heat pipes with lithium as the operating fluid have been operated successfully. A niobium-1% zirconium alloy was used for the tubes, end caps, and wick. The wick structures were formed from 100-mesh screen rolled into cylindrical tubes and inserted into the containers. Discs of screen inserted into the tubes at each end completed the structure. Both electron bombardment and induction heating were used for heat inputs. The electron-beam equipment is shown in Fig. 5.

The first model was a 38-cm-long, 1.17-cm-dia tube with a 0.064-cm-thick wall. This pipe was placed vertically in a metal vacuum chamber and heated with a 2.5-cm-dia, 2.5-cm-long electron-beam coil made of 30-mil tungsten wire. The maximum operating temperature was 1200°C. Observations and temperature measurements were made through two quartz windows (see Fig. 6). The bands on the lower portion of the heat pipe are due to different surface conditions created for emissivity studies.
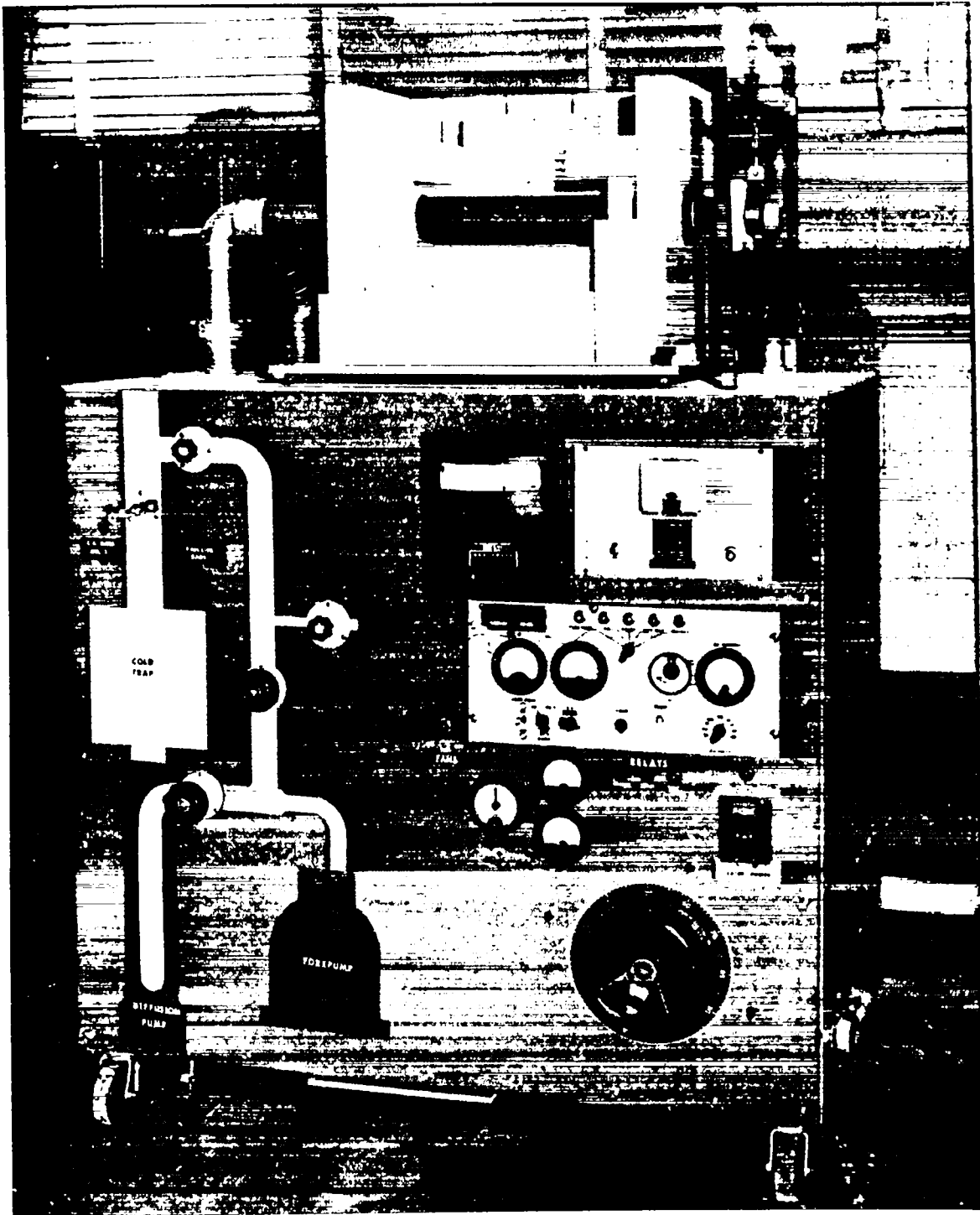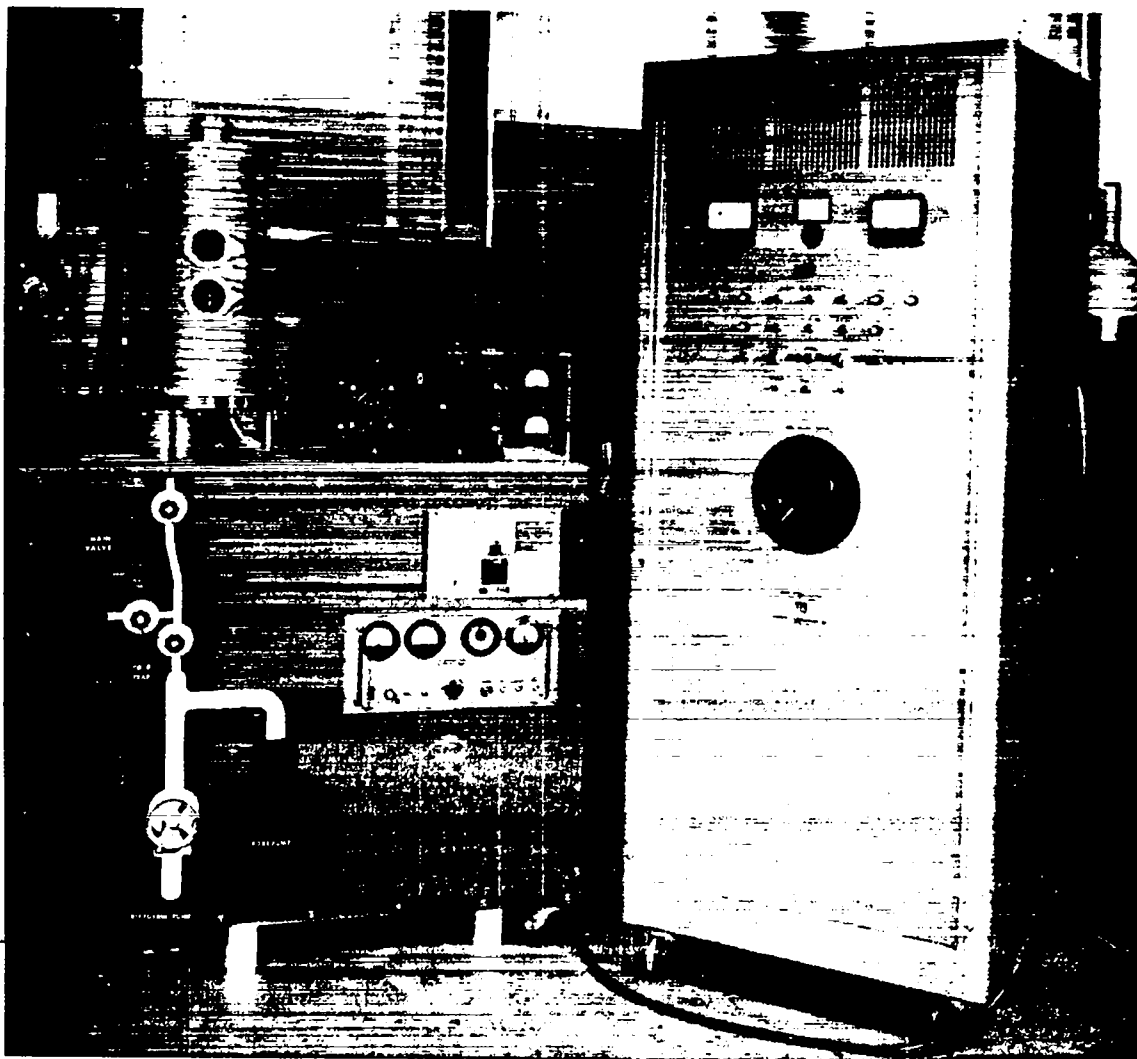
Fig. 4. High vacuum degassing furnace

Fig. 5. Electron-beam heating apparatus

Another lithium pipe, 43 cm long, was sealed under vacuum in a quartz tube (see Fig. 7). This unit was operated vertically with induction heating up to 1300°C. This is a convenient method for testing heat pipes, as it has a built-in vacuum system, is readily operated at various angles to determine wicking heights, and is small and compact. Different specimens can be readily interchanged in the induction coil. Furthermore, optical pyrometer readings can be made at the evaporator section, as there is no glare from the induction coil such as that encountered with the electron-beam heating coil. In order to increase the inductive coupling between the induction coil and the heat pipe system, a 5-cm-long, 1.6-cm-dia niobium cylinder was brazed onto the evaporator end of the heat pipe; the heat pipe extended 1.9 cm into a hole in this cylinder. (It became evident during the tests that this niobium cylinder was unnecessary.)

The niobium cylinder operated at a much higher temperature than the heat pipe because its low thermal conductivity (as compared to the conductance of the heat pipe) created a large radial temperature gradient for the amount of heat being transferred. The temperature gradient at the bottom of the pipe was due to a pool of excess liquid lithium. As only one phase of the fluid existed in this section of the pipe, isothermal conditions could not be maintained when heat was rejected by radiation.

It was interesting to note that the heat pipe could be centered in the induction coil, with respect to its length, and heat pipe action would occur in both directions. However, if the induction coil were placed around the liquid pool at the bottom of the pipe, unstable operation resulted. The pool would heat up until sufficient vapor pressure was created to suddenly force all the excess liquid to the top of the pipe. The liquid would then gradually drain down and reform the pool, which would again be heated and forced suddenly to the top of the pipe. Such cycles could be established and maintained over long periods of time. If the induction coil were positioned just above the liquid pool, normal operation occurred. This would indicate that, if there is no excess liquid in a heat pipe, heat input can be made at any section of the pipe and, if the pipe is heated at the center, two-directional operation is obtained with one evaporator and two condenser sections.

It was observed that once a wick structure has been wetted by the fluid, a heat pipe can be brought up to temperature, in a vertical position, by applying heat to a small area at the top of the pipe. There, the heat evaporates the fluid in the wick structure, forming vapor that circulates and condenses in the condenser section, raising its temperature. As the upper region of the pipe is gradually brought up to temperature, the vapor flow proceeds to sections further down the pipe, condensing and bringing those areas up to temperature. Eventually the heat pipe reaches an isothermal condition, to the limit of the wicking height attainable with the particular wick structure and fluid.

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Fig. 6. Lithium heat pipe in metal vacuum chamber

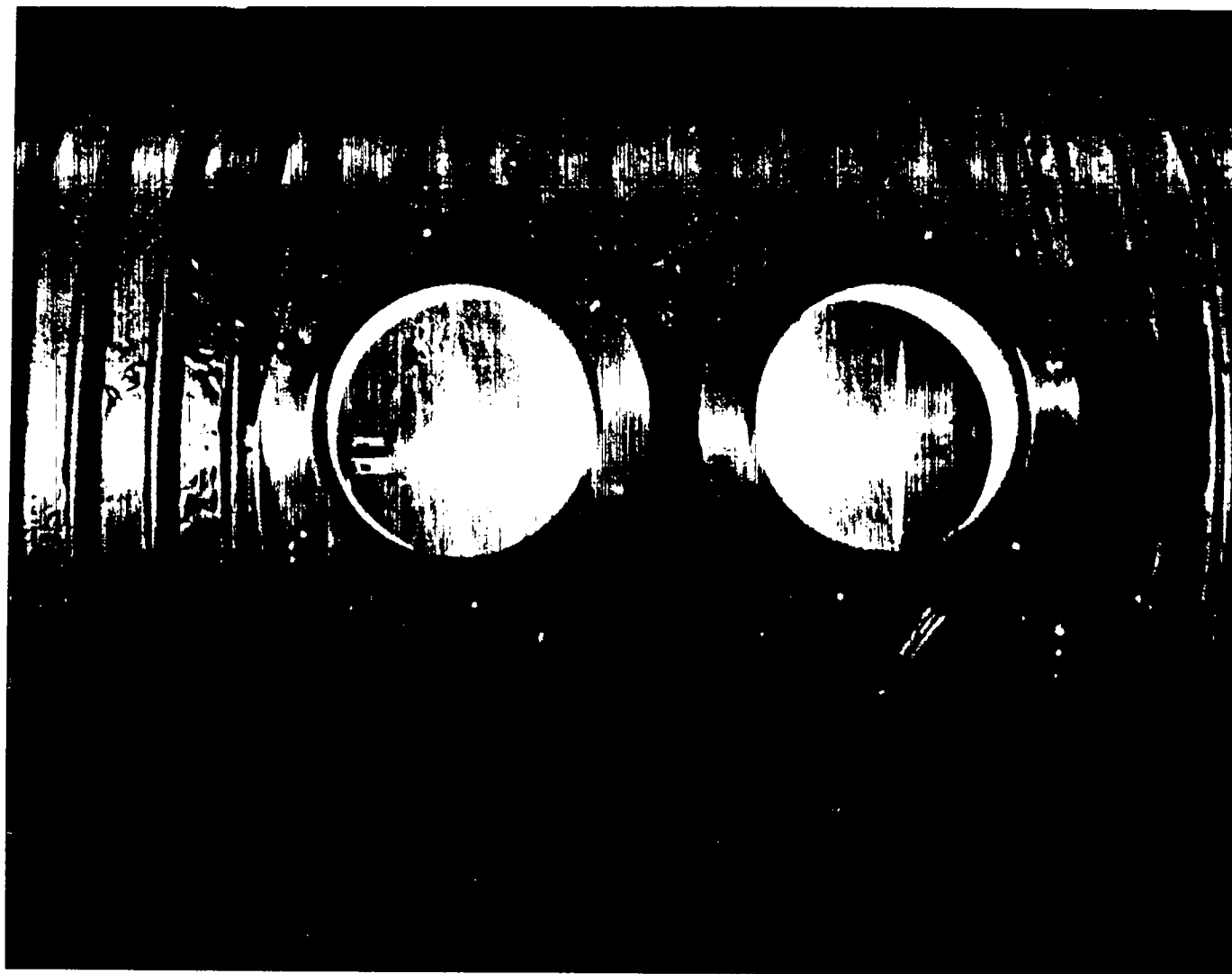Fig. 7. Lithium heat pipe at 1300°C, induction heating

Fig. 8. Silver heat pipe at 2000°C, electron-beam heating

VI. BOILING SILVER HEAT PIPES

The containers and wicks for the first boiling silver heat pipes were fabricated of pure tantalum. However, these containers sagged after operation for a few hours at 1800°C. Therefore, for greater strength, containers were made of a tantalum-5% tungsten alloy. These pipes have been operated at temperatures as high as 2000°C without sagging. The wick structure was 100-mesh tantalum screen, formed in the manner described previously. The pipes were loaded with 99.99% pure silver, following the procedure outlined for lithium pipes, except that the tubes and screen were outgassed at 2200°C. All the silver heat pipes were 1.07 cm in diameter, with lengths varying from 20.4 to 25.4 cm.

Because of the high density of silver, the pipes were operated with the evaporator ends only slightly above horizontal in order to obtain sufficient wicking action over the full length of the pipe.

Both electron-beam and induction heating were used for operating the silver heat pipes. The electron-beam coil assembly and the metal vacuum chamber used for the lithium pipes were again used; however, in the silver tests, the vacuum chamber was mounted horizontally. The silver heat pipe shown in Fig. 8 is operating at 2000°C, with electron-beam heating. The actual brightness was much greater than that indicated in the photograph, as the camera was stopped down considerably to obtain the picture. Visual observation could be made only through a dark glass, as the ultra-violet radiation transmitted by the quartz windows was intense enough to be dangerous to the unprotected eye.

VII. EXPERIMENTAL PROCEDURE

Attempts were made to evaluate the heat-transfer capabilities of the heat pipes by determining either the heat input to the evaporator section or the heat output from the condenser section.

With induction heating, it is difficult to determine heat input to the pipe accurately. The system is inefficient; the actual input is strongly dependent upon the inductive coupling between coil and pipe, and there are losses in the coil leads. Furthermore, as the wick and the liquid metal are also heated inductively, this form of heating does not simulate normal applications. For these reasons, no attempt was made to establish upper operating limits in the induction heating tests.

With electron-beam heating, a more realistic heat input value can be established: With proper electron shielding, practically all of the electron-beam power can be focused to the heat pipe. The tungsten filament radiates, however, to the heat pipe and creates an additional heat input. Therefore, the net heat input is the sum of electron-beam and filament powers, minus heat lost as radiation. Radiation shielding and thoria insulation were used to reduce heat loss (see Fig. 9).

The heat output was determined by calculating the heat rejected by the condenser section. In all the tests described in this report, heat rejection was by radiation; the accuracy of the calculations depended upon the accuracy of the total emissivity values. Knowledge of spectral emissivities was needed for accurate temperature measurement. (Although heat might have been rejected to a secondary liquid-metal or gas loop, making it easier to determine heat rejection from a heat pipe, such a system would have been much more complicated.)

A test was made to determine the maximum heat-transfer capability of a 38-cm-long lithium pipe containing two layers of screen for a wick structure. The heat-transfer capability of a heat pipe is limited by the rate at which the liquid returns to the evaporator by capillary action through the wick. If the evaporation rate of the liquid at the heat input zone exceeds the flow rate of the liquid in the wick, the wick dries out and hot spots develop. Then, the vapor flow decreases rapidly; and large temperature gradients occur along the pipe.

Below that limit, the rate of heat transfer at a given temperature is governed by the amount of heat that can be rejected from the condenser. Because heat rejection was by radiation, the controlling factor was the emissivity of the pipe surface; thus, the only way to increase the rejected heat was to increase emissivity. That can be done by roughening the pipe surface or by coating it with a material of higher emissivity. In this test, three different surface conditions were used. The first was a highly polished surface obtained with fine emery cloth and polishing compound. The second was a rough surface grit-blasted on the pipe upon completion of the first test. The third was a carbon black coating, applied after the second test had been completed.

An upper temperature limit of 1300°C was set, and the heat input was increased until this temperature was reached for each of the three surfaces, starting with the polished, or lowest emissivity, surface. It was expected that the limiting value of heat input would be indicated by the development of hot spots in the evaporator section and by a large temperature gradient in the condenser section.

To Electron
Shield
(Floating at
High Voltage)

High-Voltage
Coil Leads

High-Voltage
Shield Lead

Electron-Beam
Coil

Radiation
Shields

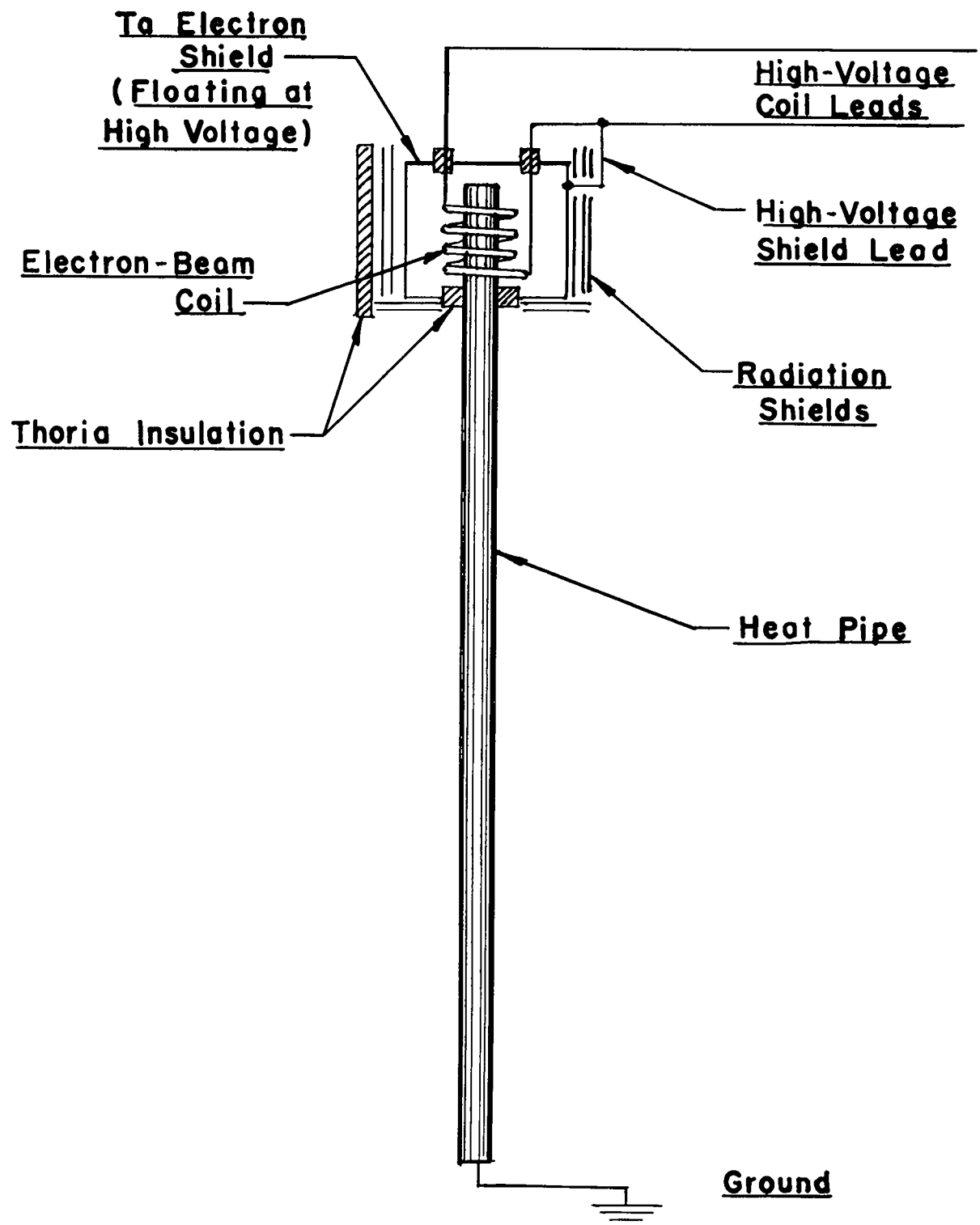Thoria Insulation

Heat Pipe

Ground

Fig. 9. Electron-beam shielding

The 43-cm-long lithium heat pipe sealed in the quartz tube (see Section V) was used to test the compatibility of the niobium-1% zirconium alloy with lithium, and to observe long-term operating stability. Because an induction heater was not permanently available, operating time had to be accumulated at intervals, resulting, of course, in many melt-freezes of the lithium.

VIII. RESULTS

Presented below are the results of various tests (described in the preceding section) to determine heat-transfer capabilities, materials compatibilities, and long-term operating characteristics.

1. Lithium Heat Pipes

Several different heat pipes were successfully operated at temperatures as high as 1300°C. Above 900°C, essentially isothermal conditions existed over the lengths of the pipes; below that temperature gradients were apparent. Below 800°C, gradients of several hundred degrees occurred.

Tests of the 38-cm-long pipe to determine its heat-transfer capability showed that operation became unstable at a heat-transfer rate of 1950 watts (corresponding to a temperature of 1250°C). An upper temperature limit of 1300°C had been decided upon for this test; and, for the polished and grit-blasted surfaces, that temperature was reached without any indication of instability. However, when the carbon-black surface was tested, the electron-beam power supply tripped at 1250°C due to excessive emission current. Several attempts were made to exceed this temperature, but the power supply tripped at the same point each time. It was concluded that the heat radiated at this temperature, 1950 watts, was the maximum heat-transfer rate for this pipe. If the heat input exceeded this value, the liquid in the wick at the heat input zone was not replaced by capillary action as rapidly as it was being evaporated; consequently, the wick dried out, and the tube-wall temperature increased considerably, causing runaway emission that tripped the power supply. Figure 10 shows radiation versus temperature for the three different surfaces.

An approximate value of heat input flux at the evaporator was calculated by assuming that all transferred heat was put into the pipe area directly under the electron-beam coil. For a 2.5-cm-long coil and with a heat input of 1950 watts, the input flux was 207 watts/sq cm. The axial heat flux is the total heat transferred divided by the cross sectional area of the pipe. At the maximum heat-transfer rate of this pipe, the axial flux was 1950 watts/sq cm; the cross sectional area was approximately one sq cm.
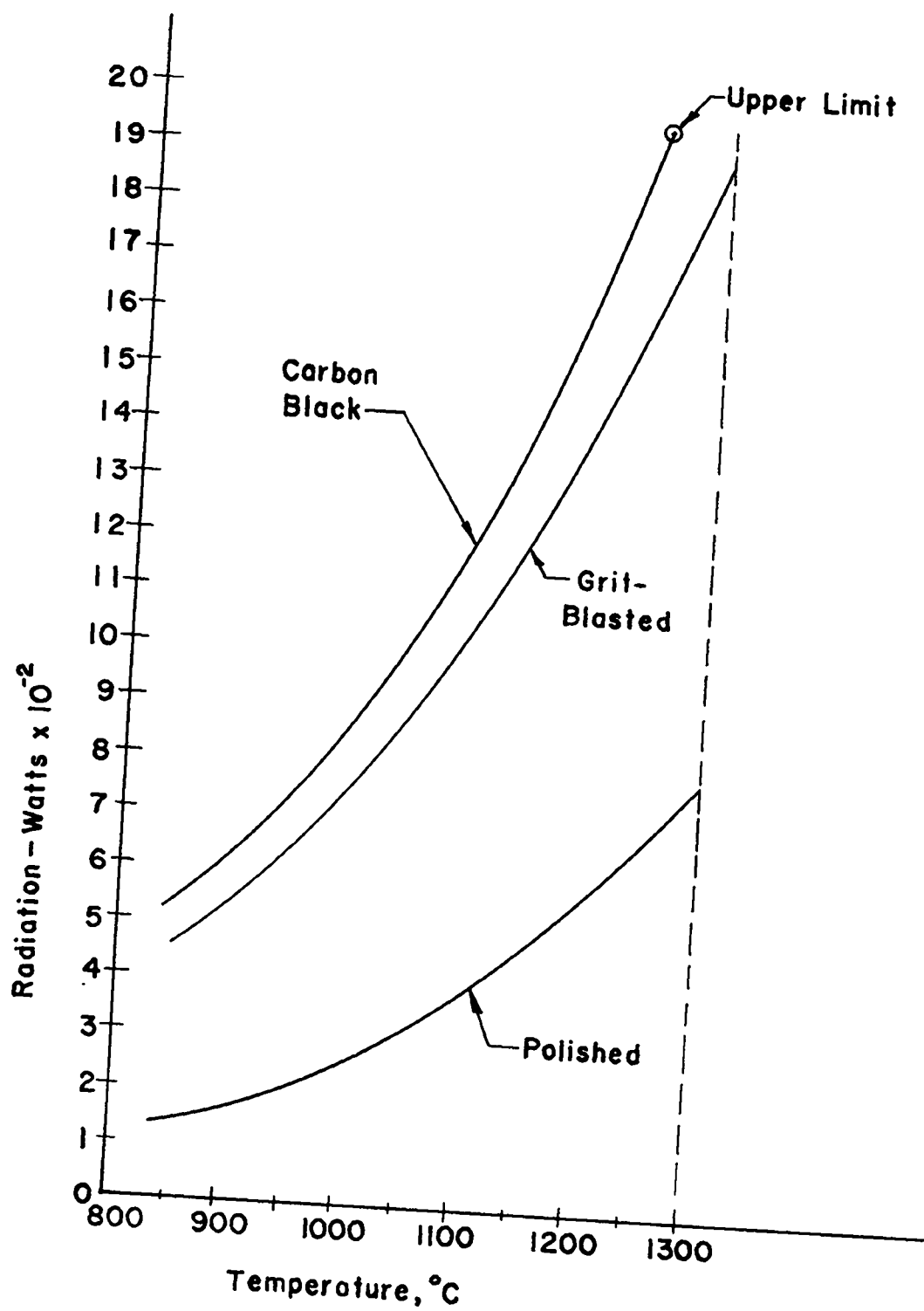
Fig. 10. Radiation from lithium heat pipe with different surface conditions

The fluid circulation rate is calculated by dividing the heat-transfer rate by the latent heat of the fluid. The volume flow rate of liquid or vapor is determined by dividing the mass flow rate by the density. At the maximum heat-transfer rate of this pipe, the fluid mass-flow rate was 0.1 g/sec. The volume flow rates were 2000 cc/sec for the vapor, and 2.7 cc/sec for the liquid. The mass flow rates in lithium heat pipes are very low because of the extremely high latent heat of lithium (see Appendix B).

Heat-transfer capacity could be increased by using more layers of screen to decrease the pressure drop of the liquid flow through the wick, allowing more liquid to flow into the evaporator section and higher heat fluxes to be reached before the wick dried out. However, two factors limit wick thickness: First, for a given tube size, a thicker wick reduces the vapor flow channel until pipe operation is limited by vapor flow. Second, a wick that is too thick can cause a large temperature drop across the liquid in the evaporator, resulting in localized boiling at the tube wall and associated hot spots.

The 43-cm-long lithium heat pipe has been operated for a total of 3500 hours at 1100°C to date. There has been no apparent change in operational characteristics, nor is there any indication of leakage. The melt-freeze cycles during the testing period have caused no damage to the heat pipe.

2. Silver Heat Pipes

Silver heat pipes were successfully operated at temperatures as high as 2000°C. Temperatures above 1500°C were necessary to achieve essentially isothermal conditions over the lengths of all the pipes tested.

At 2000°C, the heat-transfer rate of one pipe was approximately 3500 watts. By assuming that all this heat was transferred to an area directly under the electron-beam coil, the heat input flux was calculated to be 410 watts/sq cm. No unstable operation occurred at 2000°C. Tests at higher heat-transfer rates have not yet been made to determine the upper operating limit.

With a heat-transfer rate of 3500 watts, the mass flow rate was calculated to be 1.51 g/sec. The vapor and liquid volume flow rates were 8400 cc/sec and 0.167 cc/sec, respectively. The axial heat flux at the entrance to the condenser section was determined to be 4000 watts/sq cm.

Some efforts were made to run compatibility tests at 1800°C; however, difficulties were encountered because wick structures sagged away from the wall. Once this occurred, the heat pipes no longer operated properly, and large temperature gradients appeared.

The pure tantalum screen used for the wick structure apparently does not have sufficient strength for extended operations at high temperatures. Either a tantalum-tungsten alloy or tungsten will have to be used or some sort of support structure provided to hold the wick against the tube wall. Frequent shutdowns during the tests resulted in several melt-freezes of the pipes. Because of large differences in the expansion coefficients of silver and tantalum, the wick may have been distorted at those times.

IX. DISCUSSION

The major difficulty encountered in the operation of the heat pipes involved the wick structure: After extended periods of time the wicks sagged, causing inefficient operation and, in some cases, failure. It was difficult to roll the fine-mesh screen into uniform, multiple-layer cylindrical tubes and insert them into long container tubes without some resulting distortion. Although pushing a steel ball through the passage after the wick was inserted helped to press the screen against the tube wall, gaps still occurred between screen layers and between the wall and the screen. There also was a tendency for the screen to curl toward the center of the heat pipe when heated; this difficulty could be partially eliminated by inserting a tungsten helical spring inside the wick to hold it in position. In general, the rolled screen is not an ideal wick, because the geometry of the structure after insertion into the heat pipe is not known, and reproducibility is uncertain. Attempts have been made to develop theoretical equations that apply to the operating mechanisms of heat pipes; however, until a uniform, reproducible wick structure of known geometry is developed, correlation of the equations with experimental data is not possible.

Basically, the wick structure should provide axial capillary paths for the liquid flow and open radial areas for vapor condensation and evaporation. In addition, the structure should also lend itself to variations in number of capillaries, capillary diameter, and open radial area for applications over a wide range of temperatures, heat fluxes, and operating conditions. Development programs are in progress to produce wick structures that will perform these functions, yet have known, reproducible geometries.

One configuration being studied is a corrugated screen wick in which the corrugations form axial capillary paths, and the mesh of the screen provides for radial vapor flow. By varying corrugation size, different numbers of capillaries and capillary diameters result. The open radial areas for vapor flow could be varied by using different mesh screens. A single layer of corrugated screen would be adequate for many applications. The proposed configuration is relatively simple to insert into a heat pipe container. Further, if the wick were a seam-welded tube that had to be compressed slightly for insertion into the container, this prestressed condition would aid in holding the wick

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against the wall. The corrugations would stiffen the structure and decrease the tendency of the wick to sag during operation. It is possible that perforated sheet stock could be used instead of screen to simplify the corrugating process.

Another potential approach is the formation of capillaries by axially slotting the inner surface of the container wall. A sufficient number of slots of the proper dimensions provide axial wicking, and the open face of the slots allows radial flow of the vapor to and from the structure. The slots could be formed by broaching; by using different broaches, slot dimensions and numbers could be varied to satisfy the requirements of different fluids and operating conditions.

Wick structures formed by either of these methods have geometries that are measurable and reproducible, have good structural strength, and lend themselves to specific conditions. When such wick structures have been developed, it will be possible to correlate, with some confidence, theoretical equations with experimental data.

X. CONCLUSIONS

There appear to be many promising uses for heat pipes in heat-transfer situations requiring the transport of extremely high heat fluxes over wide temperature ranges. The heat pipe, because of its ability to produce isothermal conditions over large areas, may be used for the determination of total emissivities of surfaces. A discussion of this application is presented in Appendix C. The heat pipe also provides a means for concentrating the relatively low flux densities of radioisotope heat sources into small areas for the production of high temperatures. This application is described and illustrated in Appendix D.

Because the heat pipe is lightweight, has a high heat-transfer capability, and is capable of transferring heat with essentially no temperature drop, it is particularly suitable for space applications.

APPENDIX A: COMPARISON OF HEAT TRANSFER BY A HEAT PIPE AND BY A SOLID ROD

Comparison with heat transfer by conduction in a solid tantalum rod shows the superiority of the heat pipe. Assume that heat is put into one section of the rod, and the rest of the rod radiates heat into space at $0°K$ (see Fig. A-1). Also, assume boundary conditions for an infinite rod; then the temperature distribution along the rod can be expressed as:

$$t = \left[t_o^{-3/2} + \frac{3}{2} \left(\frac{8\delta E}{5kD} \right)^{1/2} x \right]^{2/3} \tag{1}$$

where:

δ = Boltzmann constant
E = emissivity
k = thermal conductivity
D = diameter

The temperature gradient at any point x along the rod is:

$$\frac{dt}{dx} = - \left(\frac{8\delta E}{5kD} \right)^{1/2} t^{5/2} \tag{2}$$

The heat radiated over a given length of the rod can be determined by substituting the expression for temperature distribution in the fourth-power radiation equation, and integrating:

$$\int_0^q dq_r = AE\delta \int_0^L \left\{ \left[t_o^{-3/2} + \frac{3}{2} \left(\frac{8\delta E}{5kD} \right)^{1/2} x \right]^{2/3} \right\}^4 dx$$

By using the resulting expression and assuming:

$t = 2000°K$
$k = 0.5 \text{ w/sq cm}/°K$
$E = 1$
$D = 1 \text{ cm}$
$L = 50 \text{ cm}$

then the energy radiated is:
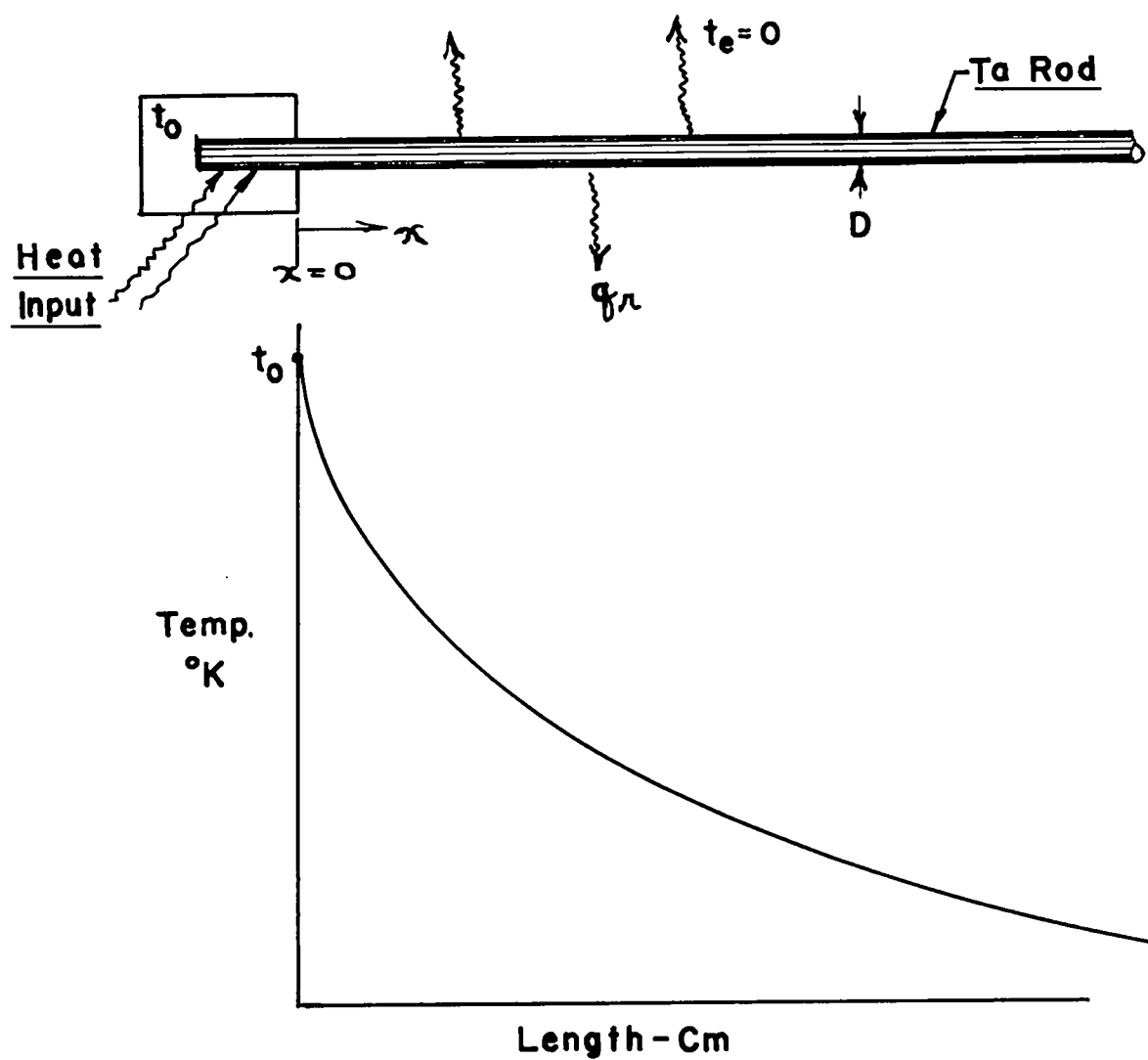
$$q_r = 307 \text{ w}$$

Fig. A-1 Radiation from solid tantalum rod

If the rod had an infinite thermal conductivity, the second term in Eq. 1 would be zero and t would equal t_o at any point x; or the rod would be isothermal. In this case the amount of heat radiated would be:

$$q_t = 30,000 \text{ w}$$

No material exists that has an infinite conductivity; however, an isothermal system can be attained by replacing the solid rod with a heat pipe utilizing mass flow of a two-phase fluid. Such a system could radiate 100 times as much heat, because the radiation temperature is constant over the length of the pipe. In the case of the tantalum rod, the temperature drops rapidly along the length, and radiation varies as the fourth power of absolute temperature.

A comparison of the tantalum rod with a silver heat pipe on the basis of heat transferred per unit weight is shown below:

	Heat Transferred (w)	Weight (g)	(w/g)
Tantalum rod	307	665	0.46
Silver heat pipe	30,000	125	240

The advantage of a heat pipe where weight is a factor, as in space applications, can be shown by the fact that it can transfer 520 times as much heat per unit weight as can a solid rod of the same cross section.

APPENDIX B: PROPERTIES OF POTENTIAL HEAT PIPE FLUIDS

	Melting Point (°C)	Boiling Point (°C)	Density (g/cc at M.P.)	Latent Heat (cal/g)	Surface Tension (dynes/cm at M.P.)
Water	0	100	1.0	538	75
Indium	156	2087	7.0	468	630
Cesium	29	705	1.8	146	55
Potassium	64	760	0.82	496	100
Sodium	98	883	0.93	1005	190
Lead	327	1737	10.5	205	450
Lithium	179	1317	0.51	4680	398
Silver	960	2212	9.3	556	930

APPENDIX C: EMISSIVITY STUDIES WITH HEAT PIPES

The heat pipe appears to have great potential for determining the total emissivities of surfaces. If a heat source is located inside a heat pipe, an accurately known heat input to the system is obtained. All of the heat input must be radiated from the external surface of the heat pipe; therefore, if the surface is isothermal and the temperature is known, the total emissivity can be determined. The heat pipe, with its two-phase fluid flow, has the ability to maintain isothermal conditions over a large area and should provide a simple, accurate method for obtaining total emissivities over a wide range of temperatures. By using various heat pipe containers and plating or spraying the containers with different materials, the emissivities of numerous materials could be established.

Known heat inputs could be provided by electrical resistance heaters or radioisotopes. The upper temperature limit would be set by the upper operating limit of the heating unit used.

One experiment of this type was performed at low temperature, with a gold-plated heat pipe containing phenyl ether. Good agreement was obtained with available emissivity values for gold, as-plated. No special precautions were taken to eliminate end losses at the heat input end. The area of the heater insert-tube opening was very small compared to the area of the test surface, so the end loss error was not very large (see Fig. C-1). The total emissivities obtained for gold, as-plated, are shown in Fig. C-2.

By using various fluids with the heat-pipe method, a wide temperature range could be covered up to the operating limits of the heat sources used. With some refinements at the heat input end, the heat-loss error could be practically eliminated. If radioactive sources were used, they could be completely sealed inside the heat pipe, as no electrical leads would be required.

APPENDIX D: CONCENTRATION OF HEAT FLUXES BY HEAT PIPES

Fig. D-1 is an example of heat pipe use: a silver pipe concentrates heat from a radiosotope to heat a small area and a lithium pipe dissipates heat from a small area to a large radiator. The application is for possible use in high-temperature thermionic emission systems. The silver heat pipe concentrates thermal energy from a radiosotope to the emitter plate, operating at 2000°K. The collector plate, maintained at approximately 1200°K to provide the necessary temperature difference for emission, is cooled by the lithium heat pipe. Feasibility studies of this application are now being made.
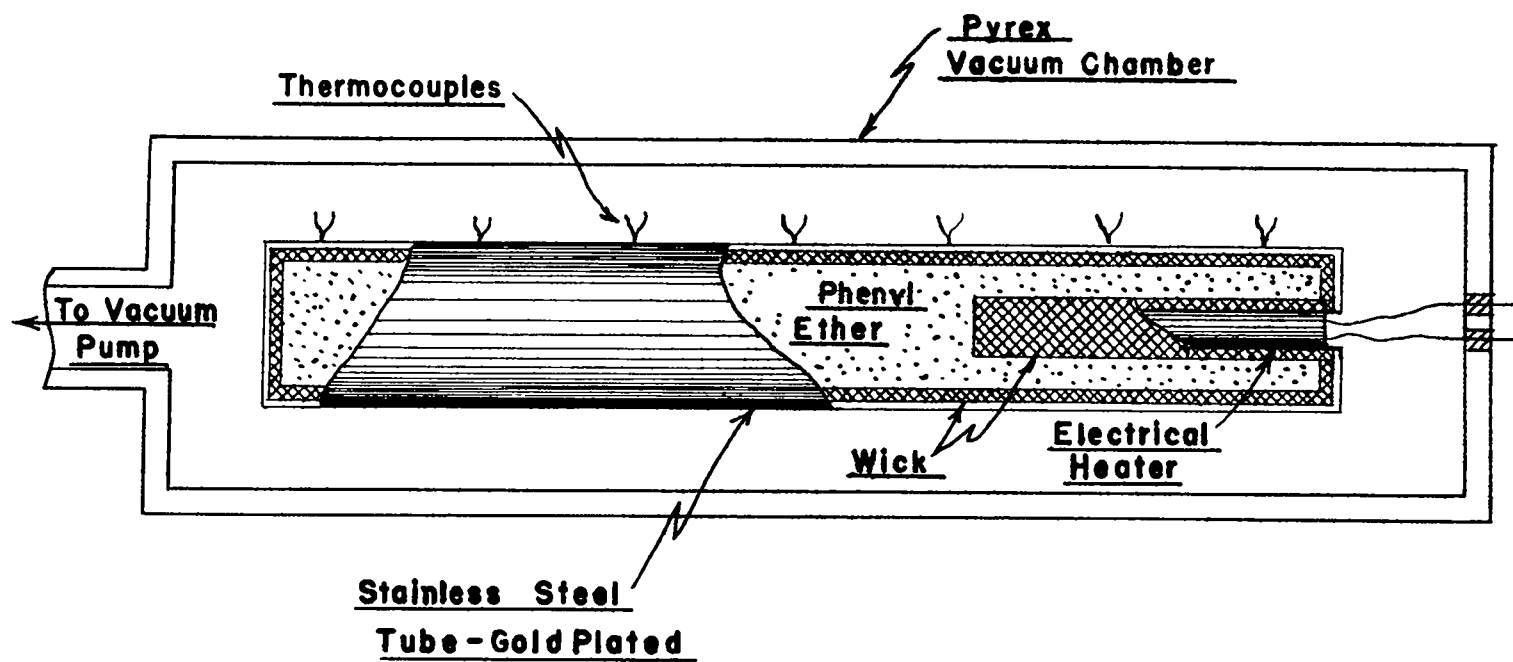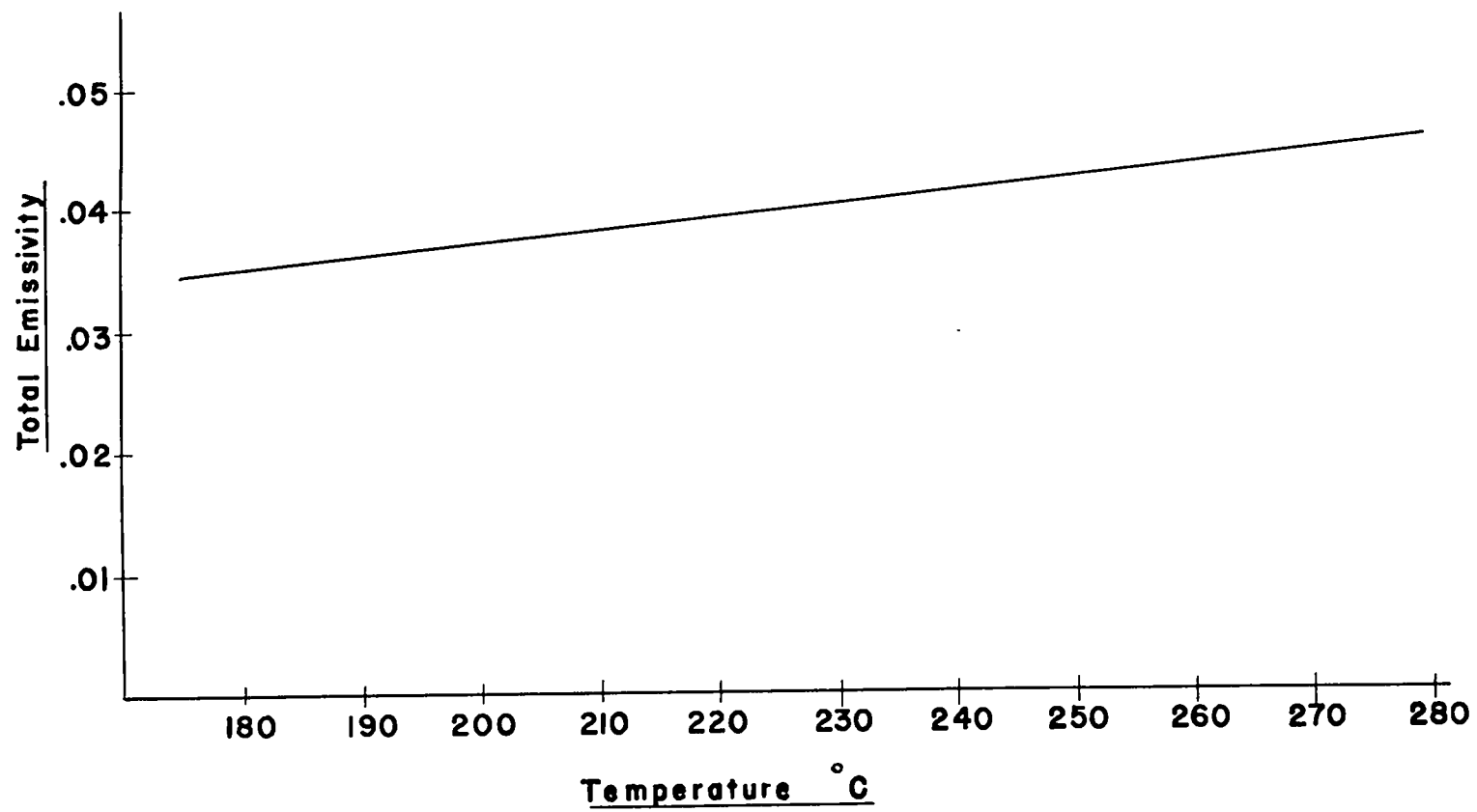
Fig. C-1   Total emissivity apparatus

Fig. C-2 Emissivity versus temperature

Ag - IN - Ta
HEAT PIPE
SOURCE

THERMIONIC CONVERTER

Li - IN - Nb
HEAT PIPE
RADIATOR

RADIATION SHIELDS
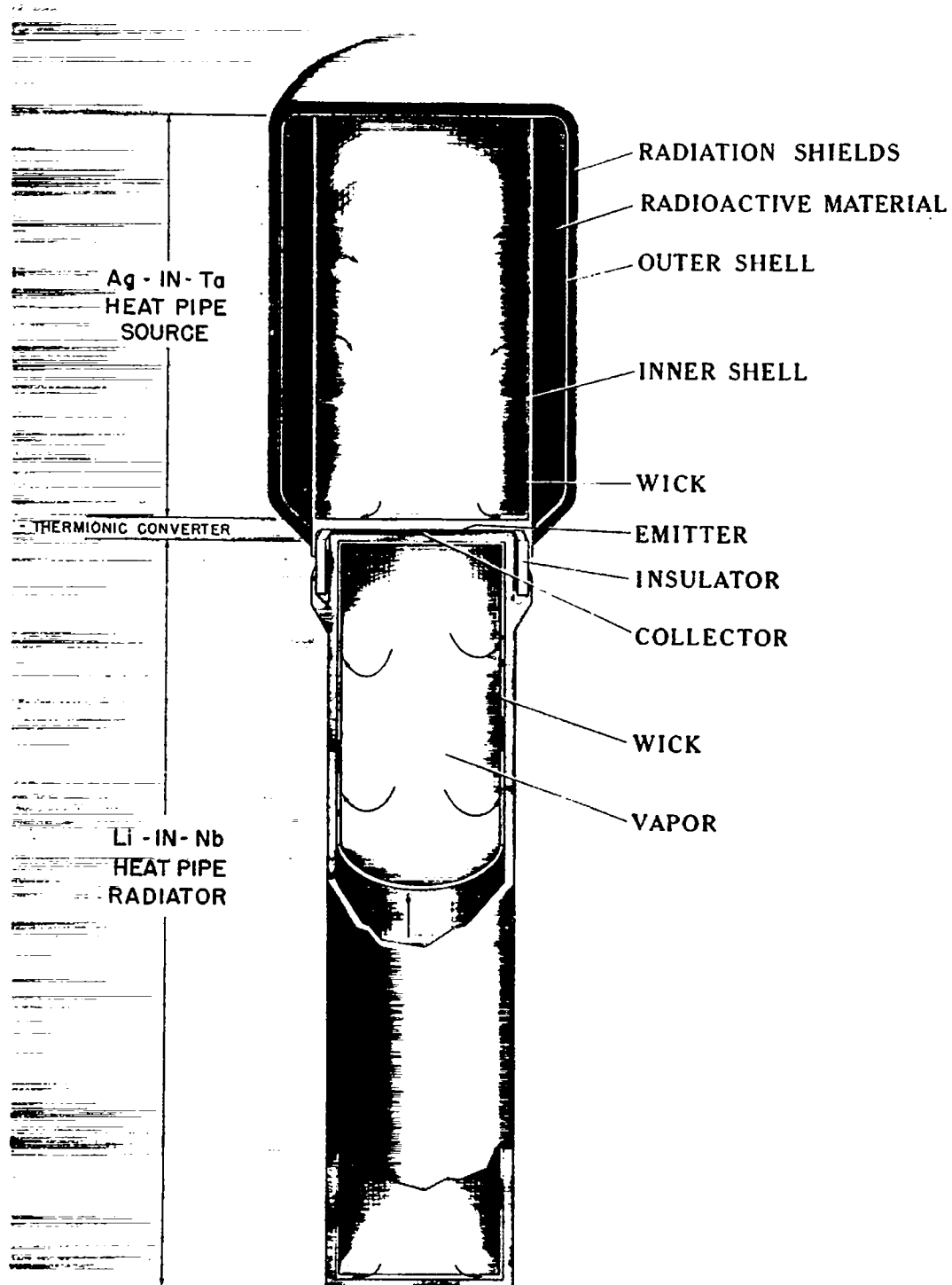RADIOACTIVE MATERIAL
OUTER SHELL
INNER SHELL
WICK
EMITTER
INSULATOR
COLLECTOR
WICK
VAPOR

Fig. D-1   Heat pipes for thermionic emitters